Calhoun: The NPS Institutional Archive

DSpace Repository

Theses and Dissertations 1. Thesis and Dissertation Collection, all items

1974

Low speed flow visulaization using holography and the development of a rapid data reduction system for holographic interferometry.

Pope, David Lawless.; Collins, Daniel Joseph.

http://hdl.handle.net/10945/17110

Downloaded from NPS Archive: Calhoun

Calhoun is the Naval Postgraduate School's public access digital repository for research materials and institutional publications created by the NPS community. Calhoun is named for Professor of Mathematics Guy K. Calhoun, NPS's first appointed -- and published -- scholarly author.

Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943

http://www.nps.edu/library

LOW SPEED FLOW VISUALIZATION USING HOLOGRAPHY AND THE DEVELOPMENT OF A RAPID DATA REDUCTION SYSTEM FOR HOLOGRAPHIC INTERFEROMETRY

David Lawless Pope

NPS-57CO74062

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

LOW SPEED FLOW VISUALIZATION USING HOLOGRAPHY AND THE DEVELOPMENT OF A RAPID DATA REDUCTION SYSTEM FOR HOLOGRAPHIC INTERFEROMETRY

by

David Lawless Pope

June 1974

Thesis Advisor D. J. Collins

Approved for public release; distribution unlimited.

T161758

Prepared for:

Naval Air Systems Command
Department of the Navy
Washington, D.C. 20360

NAVAL POSTGRADUATE SCHOOL
Monterey, California

Rear Admiral Mason Freeman
Superintendent

Jack R. Borsting
Provost

This thesis prepared in conjunction with research supported in part by Naval Air Systems Command under project order 4-1073.

Reproduction of all or part of this report is authorized.

Released as a
Technical Report by:

John M Wozencraft
Dean of Research

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NPS-57C074062	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) LOW SPEED FLOW VISUALIZATION USING HOLOGRAPHY AND THE DEVELOPMENT OF A RAPID DATA REDUCTION SYSTEM FOR HOLOGRAPHIC INTERFEROMETRY		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis June 1974 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) David Lawless Pope		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93940		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N PO4-1073
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command Deaprtment of the Navy Washington, D.C. 20360		12. REPORT DATE June 1974 13. NUMBER OF PAGES 61
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Holography, Interferometry, Flow of Visualization,

Holographic Data Reduction

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Flow visualization of low speed flow has been obtained in this thesis by the injection of a thin stream of gas. This injected gas has a refractive index which differs from that of the uniform flow in the wind tunnel. A frozen fringe hologram of the introduction of this gas indicates regions of fringe shift. A pathline is produced by connecting points of maximum fringe shift. Pathlines generated in such a manner

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
(Page 1) S/N 0102-014-6601 |

Block 20 - ABSTRACT (Cont.)

around a cylinder agree with the stream functions of potential flow theory.

A rapid means has been developed of data reduction of fringe information from a photograph of a reconstructed holographic interferogram. Data points are gathered using a digitizer and a mini-computer. The array of data points so obtained can be examined and corrected if necessary and finally expanded by means of Lagrangian interpolation. The expanded array is transferred to a fortran program which accomplishes the integral inversion and subsequently prints out the density field. By using this method of data reduction and inversion, a large time savings is realized.

Low Speed Flow Visualization Using Holography And The Development of a Rapid Data Reduction System for Holographic Interferometry

by

David Lawless Pope
Lieutenant, United States Navy
B.S., United States Naval Academy, 1967

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1974

ABSTRACT

Flow visualization of low speed flow has been obtained in this thesis by the injection of a thin stream of gas. This injected gas has a refractive index which differs from that of the uniform flow in the wind tunnel. A frozen fringe hologram of the introduction of this gas indicates regions of fringe shift. A pathline is produced by connecting points of maximum fringe shift. Pathlines generated in such a manner around a cylinder agree with the stream functions of potential flow theory.

A rapid means has been developed of data reduction of fringe information from a photograph of a reconstructed holographic interferogram. Data points are gathered using a digitizer and a mini-computer. The array of data points so obtained can be examined and corrected if necessary and finally expanded by means of Lagrangian interpolation. The expanded array is transferred to a fortran program which accomplishes the integral inversion and subsequently prints out the density field. By using this method of data reduction and inversion, a large time savings is realized.

TABLE OF CONTENTS

I. INTRODUCTION -- 7

II. FLOW VISUALIZATION --------------------------------- 9

A. HOLOGRAPHY AND FLOW VISUALIZATION ------------ 9

B. EXPERIMENTAL APPARATUS ------------------------ 11

C. EXECUTION AND RECONSTRUCTION ----------------- 13

D. COMPARISON OF RESULTS WITH POTENTIAL FLOW THEORY -- 15

E. DISCUSSION OF FLOW VISUALIZATION ------------- 16

F. CONCLUSION DERIVED FROM FLOW VISUALIZATION --- 17

III. DATA REDUCTION ----------------------------------- 19

A. RAPID DATA REDUCTION TECHNIQUE --------------- 19

B. EQUIPMENT DESCRIPTION AND OPERATION ---------- 21

C. PROCEDURE ------------------------------------- 22

D. DISCUSSION ------------------------------------ 26

E. CONCLUSION ------------------------------------ 27

FIGURES --- 28

APPENDIX A Listing of Potential Flow Program ---------- 39

APPENDIX B Listing of Calculator Data Transfer Programs ------------------------------------ 41

APPENDIX C Printed Results of Calculator Programs ----- 55

APPENDIX D Fortran Subroutine Which Inputs Data ------- 58

APPENDIX E Listing of Data in FILE FT03F001 ----------- 59

LIST OF REFERENCES ------------------------------------ 60

DISTRIBUTION LIST ------------------------------------- 61

ACKNOWLEDGEMENT

The author would like to express his gratitude to Dr. D. J. Collins for his valuable guidance during the course of this investigation, to Mr. Norman E. Leckenby for his assistance in the assembly and operation of the experimental equipment, and to my wife for her patience and encouragement.

I. INTRODUCTION

This thesis consists of two parts. The first part is an investigation of low speed flow visualization by means of holographic interferometry. The lack of significant density changes over a profile at low speeds has made interferometric investigations of low speed flow difficult. In this study, flow visualization at low speeds has been obtained by injecting a thin stream of gas in the wind tunnel. This gas had a refractive index which varied from that of the uniform flow in the wind tunnel. A frozen fringe hologram of the flow field with the introduced gas indicated regions of fringe shift. The pathline can be found by connecting points of maximum fringe shift. Pathlines generated in such a manner were compared with potential flow theory by superimposing a family of stream functions over the experimental pathline. This comparison was done with a cylinder profile in a uniform steady flow.

The second part of this thesis concerns itself with a rapid means of data reduction of the large amount of fringe data that is obtained in holographic interferometry. A digitizer and a mini-computer were used to effect this rapid means of data reduction. The number of data points is expanded in the mini-computer by using Lagrangian interpolation. The whole array of points are also automatically transferred to a fortran data reduction program. This existing fortran program then inverts the integral equations to determine the

density field. In the past, fringe data had been collected from a hologram by the use of an optical comparator to determine the amount of fringe shift along each plane. The data was typed onto IBM cards and fed into a fortran program for reduction. The present development of the use of a digitizer and the ability to automatically feed data into a fortran program greatly reduces the time to obtain a density field from a hologram.

II. FLOW VISUALIZATION

A. HOLOGRAPHY AND FLOW VISUALIZATION

Dennis Gabor in 1948 (1) was the first to invent a method of wavefront reconstruction called holography. With the development in the early 1960's of a coherent source of radiation, the laser, the field of holography rapidly developed.

Holography is the process of storing wavefronts in a photosensitive material called a hologram. At a later time these wavefronts may be reconstructed from the hologram to form an image which has the same depth and parallax characteristics as the real object. This is accomplished by recording the interference pattern between the light diffracted by the object and a reference beam of light. An optical arrangement is set up to split the coherent light source into a reference beam and a scene or object beam. Within certain restrictions the paths of these two beams are arbitrary. The photosensitive plate is placed in such a position that the reference beam and the diffracted light from the object fall upon it. As stated in Ref. 1, each point on the hologram contains the full information of the object as seen from that point. Full information constitutes intensity and phase information. The phase information is derived from the interference pattern. When the object is reconstructed, each of these points superimposes its own complete picture, which has depth and parallax. The recording of phase information (with the associated depth and parallax) is what

distinguishes holography from photography which only records intensities.

A frozen fringe hologram is one which has been doubly exposed. One exposure records the reference situation. The second exposure records whatever perturbation has been introduced. In the present low speed flow visualization experiment the reference condition of exposure is the steady flow of uniform gas over the two-dimensional profile. After the reference exposure an optical component is moved slightly to provide fringe lines. The flow field is perturbed by the introduction of a thin stream of gas into the uniform steady flow ahead of the profile. A second exposure is taken on the same hologram plate of the perturbed flow. In the reconstruction of the resulting hologram, the two recorded flow fields interfere with each other and show a deviation in the superimposed finite fringes. Since both exposures utilize the same optical components, the fringe lines are lines of constant differences in optical path lengths. Any imperfection in the optical quality of the apparatus is thus eliminated.

When a gas of a different density (optical path length) is carefully introduced into the flow field, it is swept through the wind tunnel and follows a pathline. Holography is extremely sensitive to variations in optical path length and by using holographic techniques a line of fringe shifts can be seen in the region of the injected gas. By carefully adjusting the amount of gas introduced in relation to the

wind tunnel velocity, a small well defined line of fringe shifts can be produced. A pathline can be created by connecting points of maximum fringe shift.

B. EXPERIMENTAL APPARATUS

The arrangement of the experiment is shown in figure 1(a). This type of set-up is known as a modified Z-Type Schlieren. A Korad Q-switched laser (ruby wave length 6943 Å) is mounted on an optical rail. A small five-milliwatt helium-neon continuous gas laser is placed adjacent to the rail to provide alignment of the optics. The beam is expanded and projected onto a parabolic mirror. This mirror collimates the beam to facilitate easier reconstruction. The reference beam travels through the beam splitter and is reflected off two mirrors before illuminating the holographic plate. The object beam is reflected off the beam splitter and then projected through the wind tunnel. Just before the tunnel the object beam passes through a diffusing plate and a grid. The actual exposure time with the Q-switched laser was on the order of twenty nano-seconds. This stopped all movement during the exposure, but did not prevent movement between exposures. The tunnel was mounted separately from all other components to minimize unwanted movement caused by vibration. Alignment of the optics was done by projecting the small laser beam through the ruby laser head and out into the optical system. The initial alignment of the small laser with the Q-switched laser was accomplished with burn holes in photographic paper. This technique is explained in Appendix A of Ref. 2. Fringe

lines were formed by moving the beam splitter .003 inches between exposures. The beam splitter was mounted on a precision X-Y translating stage.

The wind tunnel is 3.5 inches by 3.5 inches and constructed out of plexiglass (not of optical quality). The speed of the tunnel can be varied from zero to twenty-two feet per second. A section of honeycomb was placed at the entrance to serve as a flow straightener and as a support for the tube which injects the gas.

The tube used for injecting the gas had an outside diameter of 3/32 inches. It was connected by tubing to a flow meter. This meter allowed visual adjustment of the injection gas flow rate.

Two profiles were used, both constructed from plexiglass. Pictures of the profiles and their supports are shown in Fig. 1(e). A cylinder was used having a length of three inches and a diameter of one inch. The second profile was a wing having a length of three inches, a chord of 1.5 inches and a thickness of 3/16 inches. Both profiles were supported by two upright pieces of plexiglass. A grid was lightly inked onto the supports to provide a reference during reconstruction. The ends of the profiles were painted black for better definition of their outline. There was a snug fit between the pins, which extended from each end of the profiles, into the two supports. This fit allowed the wing to be set at a desired angle of attack and remain there. When the profile was adjusted between the supports then the assembly was slid

into the tunnel. The honeycomb was placed at the entrance and the injection tube inserted through the honeycomb.

Reconstruction was done with a fifteen-milliwatt helium-neon laser. The beam was expanded from .04 inches to .25 inches by the use of two mirrors. A sketch of the reconstruction is shown in Fig. 1(d). A shutter was placed between the second mirror and the hologram plate holder. In order to photograph the real image the camera lens was removed. A dark cloth was used to cover the laser and prevent any extraneous light from overexposing the film.

Other equipment used in this experiment:

1. power supply and circulator for Q-switched laser
2. eye protectors
3. Agfa 10E75 holographic emulsion plate and Polaroid Type 55 film
4. auto collimator for internal Q-switched laser alignment.

C. EXECUTION AND RECONSTRUCTION

Before taking a frozen fringe hologram, the alignment of the optical system was verified using the small 5-milliwatt laser. While this was being done the power supply for the Q-switched laser was turned on. The recommended warm-up time for the power supply is five minutes. The circulator was also turned on to stabilize the laser head and the etalon at a low temperature. A small amount of air was blown onto the optical surfaces to remove dust. The mirror directing the alignment beam through the ruby was removed and a 2.5mm

transverse mode selector pin hole was placed in its holder. The Agfa 10E75 emulsion plate was placed in the plate holder which was under a dark cloth. After appropriate warnings to other personnel in the area and donning safety glasses, the laser was charged. The wind tunnel was set at the desired speed and allowed to stabilize. The black cloth covering the holder was removed, the laser fired, and the black cloth replaced. Then the beam splitter was moved .003 inches. The injection gas was turned on and the flow regulated. The capacitor bank for the laser was again charged and, after removing the cloth, fired. The laser, wind tunnel and the injection gas were turned off while developing the emulsion plate.

Emulsion plate development was standard:

1. Kodak D-19 developer for five minutes
2. acetic acid stop bath for thirty seconds
3. fixer for five minutes.

The plate was washed in water followed by a rinse in Kodak Photoflo wetting agent. A hot air dryer was used to dry the plate. Occasionally the plate was overexposed and a bleach was used. Whenever this was done an index matching solution of xylene was also used to reduce the noise level of the hologram. Further information on bleaching and index matching is available in section 10.8.5 of Ref. 1.

Reconstruction was done with a fifteen-milliwatt Stabilite laser using the setup explained in section B and illustrated in Fig. 1(d). The virtual image was quickly

reconstructed to assess the quality of the hologram. This was easily done by using the collimating lens of the Stabilite laser and looking through the hologram. If the quality of the plate warranted a photographic record then the plate was reversed in its holder. The collimating lens was removed from the laser and the beam was slightly expanded to reduce speckle. The virtual image was projected onto the frosted glass at the back of a lensless camera. For a discussion of real and virtual images the reader is directed to Ref. 1. An f-16 aperature was used on the shuttering device. Black cloth covered the camera, holder, shutter and the laser. The plate holder was adjusted to present the correct picture on the ground glass of the camera. A photographic record was made using Polaroid Type 55 positive/negative film.

D. COMPARISON OF RESULTS WITH POTENTIAL FLOW THEORY

Two-dimensional potential flow theory was used to give a comparison of experimental pathlines obtained by connecting points of maximum fringe shift. A discussion of this theory is presented in Ref. 4.

The program listed in Appendix A calculates stream functions of uniform flow past a circular cylinder with circulation. The stream function ψ is given as:

$$\psi = Uy - U\frac{a^2 y}{r^2} + \frac{\tau}{2\pi} \ln\left(\frac{r}{a}\right)$$

where U = uniform velocity ; $r = \sqrt{x^2 + y^2}$;

a = cylinder radius; τ = circulation.

An example of the graphical output of a cylinder with circulation is shown in Fig. 2(c). In the experimentation for this thesis there was no circulation around the cylinder.

When the photograph of the cylinder in Fig. 2(a) is superimposed over the stream functions calculated from the program in Appendix A then Fig. 2(d) is the result. Notice the close agreement between the stream function labeled β and the points of maximum fringe shift over the profile. Downstream of the cylinder the shift in the stream function β is believed due to the heavier carbon dioxide used as the injected gas. As the wind tunnel speed is increased the point of divergence of the injected gas with the stream function is shifted further downstream. It was found that for very low tunnel speeds the fall of the carbon dioxide occurred at earlier points. At wind tunnel speeds of 22 feet per second the line of fringe shifts caused by injecting carbon dioxide agreed favorably with a stream function over a cylinder.

E. DISCUSSION OF FLOW VISUALIZATION

Three types of injection gases were investigated. Helium, argon, and carbon dioxide were introduced into the flow field. Helium and carbon dioxide provided an acceptable fringe shift. The most advantageous gas was carbon dioxide since its high molecular weight prevented the injected stream from rapidly diffusing in the tunnel. Fig. 2(a) shows that this fringe shift is small and well defined over the profile.

To accurately define the pathline the injected gas must be swept through the tunnel. If the flow rate out of the injection tube is too high, then the subsequent path of the gas does not follow a pathline. To ensure pathline accuracy the velocity of injection gas is matched as closely as possible to the velocity of the tunnel. Both the tunnel velocity and the injected gas velocity were 22 feet per second. Velocity matching required calibration of both the wind tunnel and the injection flow metering device. Once the velocities are matched then the amount of gas injected is dependent on the injection tube diameter. At low speeds a tube which had a diameter 5% of the height of the tunnel was able to define a fringe shift throughout the hologram. At higher tunnel speeds a smaller tube can be used since the gas flow rate is increased and more gas is introduced to cause a shift. Fig. 2(b) is an example where the flow velocities were not matched. Notice in the figure how the injected gas is blown onto the lower surface of the wing. The Kutta Condition is easily recognized in the circled area at the trailing edge.

F. CONCLUSION DERIVED FROM FLOW VISUALIZATION

The sensitivity of holography to slight variations in density makes this flow visualization technique ideal for low speed flow investigation. Depending on the nature in which you inject the gas one can emphasize different features of the flow. Although it was not done for this thesis,

perhaps vortices can be visualized by injecting more gas. As shown by Fig. 2(a), when the velocity of the injected gas is matched to that of the wind tunnel the resultant line of fringe shift makes a pathline visible around the profile.

III. DATA REDUCTION

A. RAPID DATA REDUCTION TECHNIQUE

Due to the large amount of data generated by holographic interferometry, a rapid means of data reduction is desired in the determination of a density field from holography. To date the emphasis has been on developing a better fortran program which inverts the integral equations in a calculation of a density field. A comparison of the different methods used to invert the integral has been discussed by Sweeney [Ref. 6]. This paper addresses the problem of data acquisition and transfer of these data to a fortran inversion program. A digitizer is used in determining the fringe shift in an interferogram obtained by reconstructing the frozen fringe hologram. A mini-computer processes the data using Lagrangian interpolation, and then stores it. At an appropriate time the data are recalled from the storage tape cassette in the mini-computer and automatically transferred to a large computer for density calculation. In the previous method of data reduction the fringe data had been collected by the use of an optical comparator which determined the amount of fringe shift along each plane of a hologram. The fringe data were then typed onto IBM cards and submitted to a fortran program in a large computer. The present development of the use of a digitizer and the ability to store data and then automatically transfer it to a fortran program greatly reduces the time needed to obtain a density field.

To obtain a photograph of fringe data, a doubly exposed hologram is taken of the aerodynamic phenomenon. The first exposure is of the reference condition which usually is a no-flow situation. Flow is then introduced into the area in question and a second holographic exposure is taken. Finite fringe lines are established on the hologram by a slight movement between exposures of an optical component. The holographic plate is developed and then the scene is reconstructed using a laser source. A photographic record can be taken of the real or the virtual image. For a further explanation of holographic interferometry the reader is directed to Ref. 5.

The actual integral inversion in the fortran program can be done in many ways. A comparison of different methods has been discussed by Sweeney [Ref. 6]. Some of these methods are:

1. Representation of the integral by orthogonal polynomials
2. Fourier Expansions
3. Fourier Transforms
4. Fast Fourier Transforms.

The overwhelming amount of data generated by holographic interferometry requires a rapid method of data acquisition, evaluation, storage, and transfer.

B. EQUIPMENT DESCRIPTION AND OPERATION

This data reduction technique uses a Hewlett Packard digitizer (HP9864A), calculator (HP9830A) and printer (HP9866A). A photograph of the apparatus is shown in Fig. 3. An acoustic coupler was also used to allow the calculator to act as an on-line terminal with the Naval Postgraduate School IBM 360 computer. The power supply for the digitizer was mounted under the table and the printer, as can be seen in Fig. 3, is resting on top of the calculator.

Data were introduced into this equipment with the use of the cursor attached to the digitizer. A button is on the cursor which defines the origin on the magnetic table. The coordinates of single points are entered by depressing button "S". Continuous points can be entered by depressing "C". This last feature was not used in the program.

The programmable calculator uses Basic language and has an initial memory capability of 1760 words. Additional memory can be added externally or internally to the calculator. A tape cassette with 32,000 word storage capacity can be used with the calculator. Program or data can be stored on or retrieved from this cassette. The entire program is on the first portion of this cassette. The remainder of the magnetic tape is used to store information for up to nine pictures, each picture containing twenty fringe lines and twenty planes. By employing a Terminal Read-Only-Memory (Term ROM) the calculator becomes an on-line terminal for an IBM 360 computer. While in the Term ROM mode the calculator

retains its basic operating ability. It is possible, although not advisable, for an operator to execute a terminal command and while the IBM operation is being performed, use the calculator locally. Operation of the calculator as a terminal was in accordance with the normal terminal procedure.

C. PROCEDURE

The procedure of using this method of data reduction is extremely straightforward. A listing of the programs to transfer data is given in Appendix B. Each of the six programs is stored in a file on a tape cassette. Each program is referred to by the cassette file in which the program is stored. The arrangement of the programs were designed to allow an operator to collect and expand fringe data for up to nine pictures. At a later time, when the terminal mode for the IBM 360 is available, then the stored data are sent to the large computer for reduction. A flow diagram of these operations is shown in Fig. 4. A description of the procedure used in the data reduction follows.

A photograph of a frozen fringe hologram was taped to the table of the digitizer. If the hologram did not have a well defined grid than a thin transparent grid was taped over the photograph to provide a reference. The calculator, printer and digitizer were turned on. The data reduction tape cassette was placed in the calculator and the command "LOAD" was executed. The program was started at point A on Fig. 4 by executing the command "RUN". Statement 20 requested

the operator to enter the time, day, month and year. These numbers were introduced into the calculator by typing them onto the display. All numbers were separated with commas. The display was executed and the program (HP file 0) continued to run. HP file 0 printed the time, day, month, year, and the program organization. At statement 190, HP file 1 was automatically retrieved from the cassette and loaded into the calculator. HP file 1 asked for the orientation of the grid. The origin and an arbitrary second point on the horizontal axis were entered by depressing the cursor "O" (for the origin) and then the cursor "S". By lifting the cursor $\frac{1}{4}$ inch off of the table the established origin was erased and the orientation procedure had to be repeated. Whenever the calculator is ready to accept a data point from the digitizer a soft beep is heard. The calculator asks for the number of fringe lines to be used from the picture. Next the number of planes in the picture is entered. The program is able to accept up to 20 fringe lines and 20 planes. The equation of each fringe line is entered by entering two arbitrary data points on the line in the linear region. After all lines were entered the program prints the mean and standard deviation of the slopes of all lines. Also the differences from the mean of each slope are printed. The operator makes an evaluation as to the validity of his fringe lines by comparing the slopes. If any slope varied greatly from the mean then all fringe lines can be reentered. An example of the printout is shown in Appendix C. If the fringe lines

are satisfactory then "CONT" was executed and HP file 2 is loaded into the calculator. The picture number and the number of data points in each plane are entered. As each data point is entered the elevation and fringe shift are printed. At conclusion of each plane the array of elevations and shifts are stored on a cassette tape file. The first number in the array is the number of data points in that plane. The second number in the array is the elevation of the first data point. The third number is the fringe shift for the first data point. Elevations and shift alternate through the remainder of the array.

The reference file is filled after acquiring all the data points in the picture. The reference file must be compatible with the fortran data reduction program. A program based on Fourier Transform methods, [Ref. 3], was modified to accept data input parameters in a specific order. After the reference file is filled, it is stored in the cassette under the appropriate picture number. The parameters in the reference file are shown in Appendix B, file 2 starting with statement 430. The operator was at point B in Fig. 4. Either he can gather more data from different pictures or expand the data for fortran reduction.

HP file 4 is loaded for data expansion. Expansion is done using Lagrangian interpolation. All of the data points from the plane to be reduced are printed out. The program asks for the data point numbers which will be the basis of the array of expanded data. The number of points to use for

curve fitting should be less than seven. If a greater number of points are used then the computational time greatly increases but more importantly the curve fit to the data points is erratic. If more than one picture needs to be reduced then the same point numbers are automatically used for data expansion of each picture. The first number in the expander array is the number of data points to follow. The second number is the number of the plane in the picture. Before the expansion of the array all positions were initialized to 9.99999. This is shown in File FT03F001 of Appendix E where the actual data that has been fed in are indicated and those positions in the array that are not expanded data are 9.99999. The reason for initializing the array is for convenience of data transmission. The absence of the nines following the array should be investigated by reading out the stored data. After the expanded data points are stored in the cassette the operator loads HP file 3.

File 3 is the program which automatically feeds the data into the fortran system. Directions for its use are printed by executing "LIST 10,110". To reduce the transmission time the expanded data is sent to the IBM 360 in arrays of six numbers. The arrays of six numbers are placed on a storage disk in the IBM 360 system under a file labeled "FILE FT03F001". The fortran reduction program calls FILE FT03F001 for its data input.

D. DISCUSSION

The previously described technique permits extremely rapid data acquisition and transfer. The ability to rapidly acquire, transfer, and store fringe data in large quantities allows the operator to process many holograms. To determine a density field around an asymmetric object in a wind tunnel, as many holographic views as possible are used. Each of these holograms is taken at a different angle and provides fringe data as seen from that angle. This program has the ability to process nine holograms of 400 data points each.

An improvement of this data reduction method can be made by incorporating a plotter peripheral and by developing a better interpolating routine. At present the expanded data is based on six fringe shift data points. When more than six points are used the expanded array becomes erratic. One would like to utilize as many of the available 20 data points as possible on each plane. A new interpolating routine could be developed to accept more than six points and still yield accurate results. The expanded array and the original data points could be compared on the plotter. From the graphical output of the plotter an improved subset of data points could be chosen to expand the array. By incorporating this scheme not only the best order polynomial is used to expand the data but also the best set of data points.

With the ability to evaluate and store up to nine sets of fringe data on a cassette, valuable operator/computer time is not lost transferring and correcting fortran input data.

E. CONCLUSION

A procedure for rapid fringe data collection, transfer and storage has been accomplished. With slight modification, this procedure is applicable to all fortran data reduction techniques. With one photograph of 20 fringe lines and 20 points, the use of a digitizer was 20 times faster than that of an optical comparator. This was assuming the optical comparator was used in conjunction with a programmed desk calculator to calculate fringe lines and fringe shifts. The amount of time in the transfer of data to the fortran program was 15 times less by using this technique. When many pictures are taken to completely determine the density field around an object, the magnitude of time saved is very large.

The ability to rapidly store and transfer the large amounts of data obtained from a finite frozen fringe hologram results in a considerable time savings.

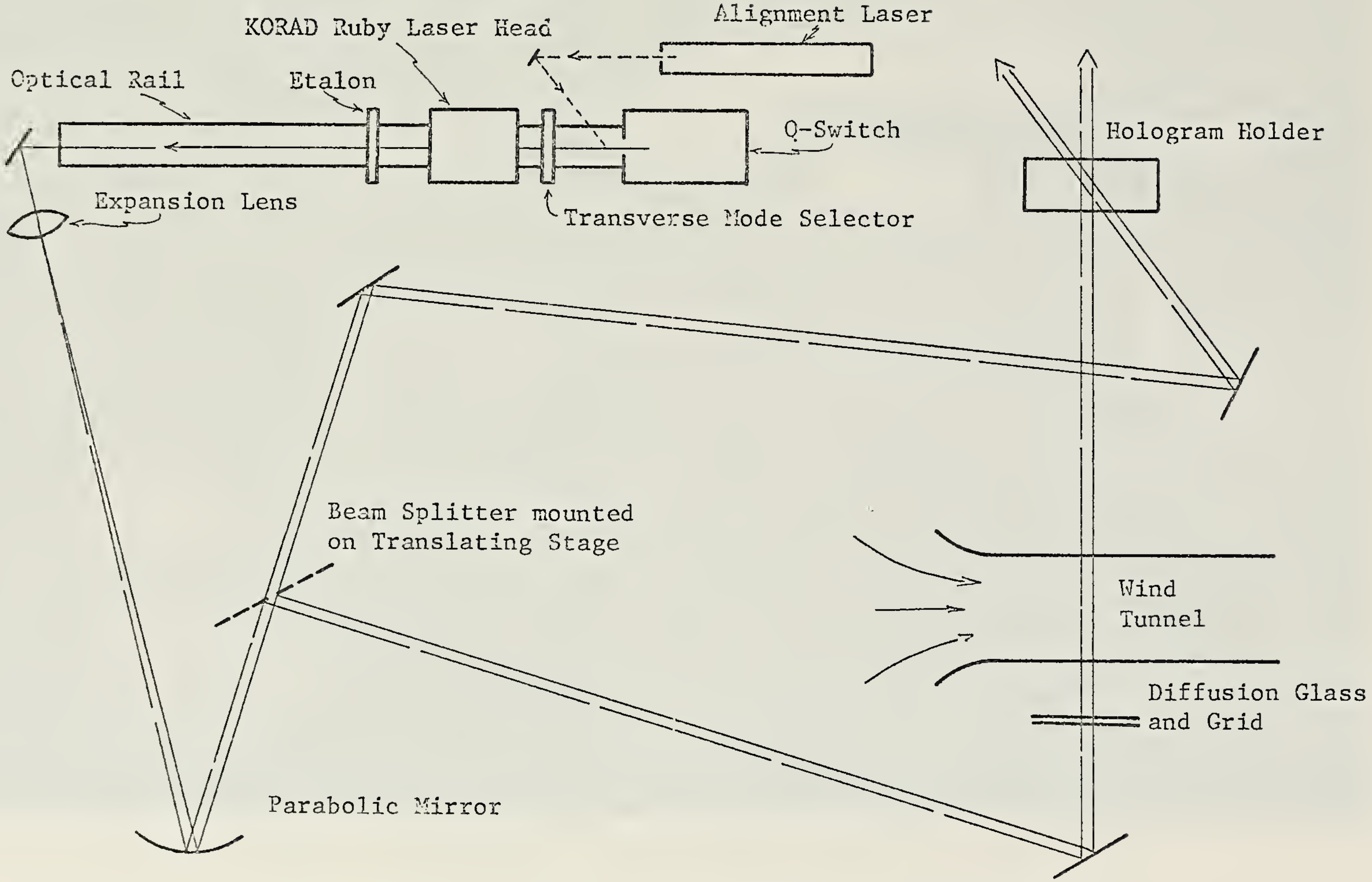

Figure 1(a). Schematic of holographic arrangement.

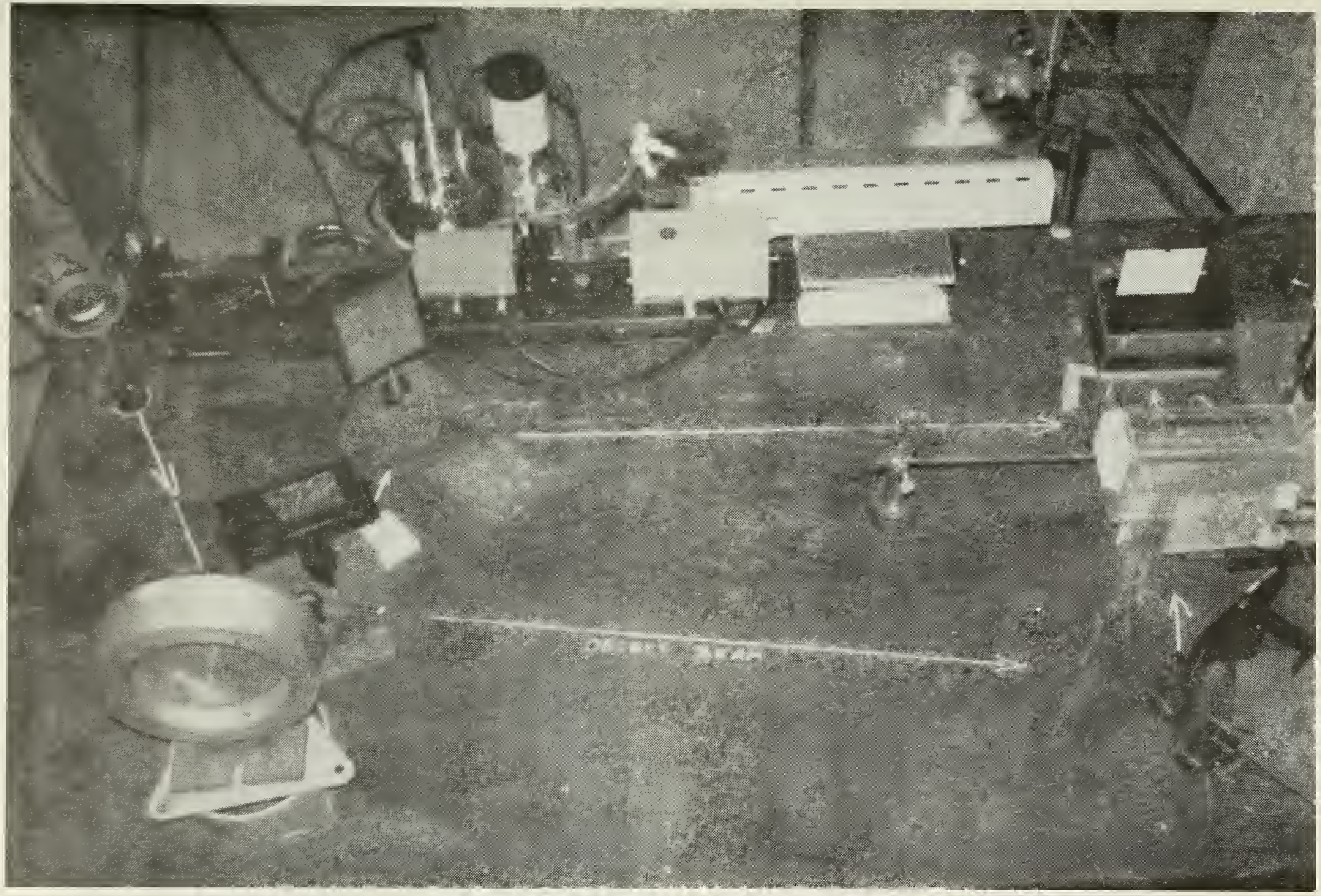

Figure 1(b). An overall view of the holographic experiment

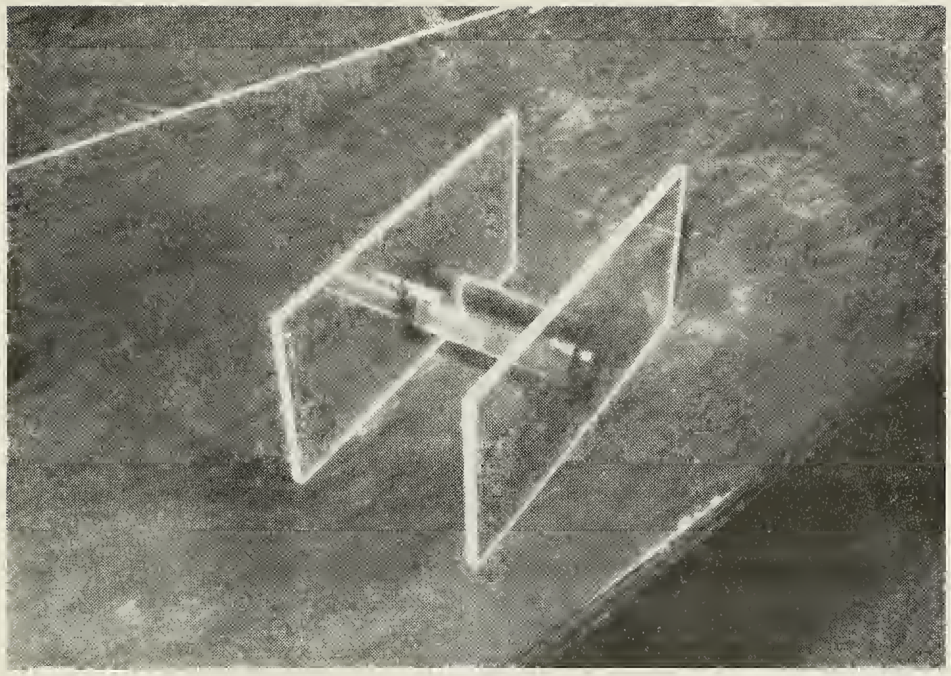

Figure 1(c). Cylindrical profile mounted between plexiglass supports

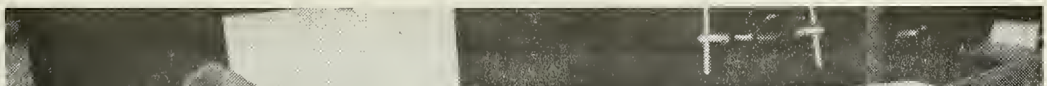

Figure 1(d). Profile and supports inserted in tunnel. Notice honeycomb and injection tube.

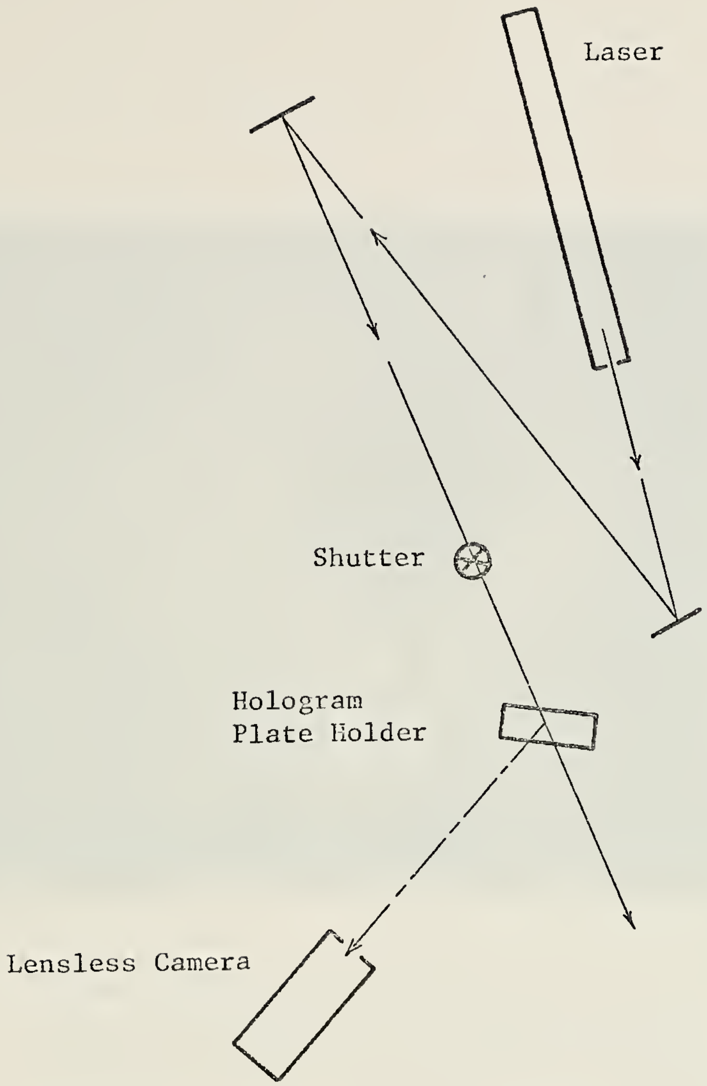

Figure 1(e). Schematic of reconstruction of a hologram.

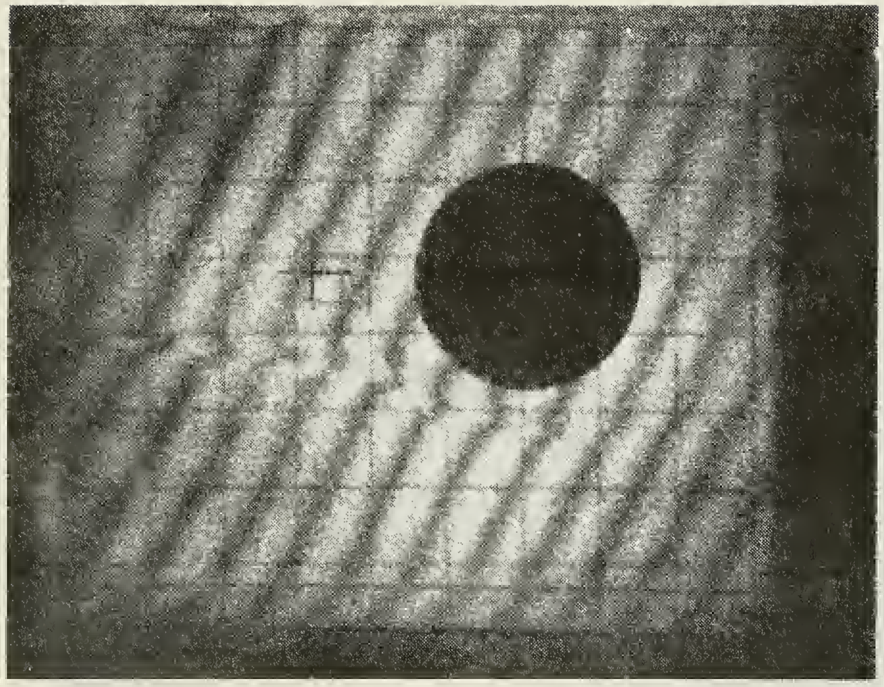

Figure 2(a). Photograph of a reconstructed hologram of a cylinder in a uniform flow of 22 fps. Notice the line of fringe shifts over the profile caused by the injection of a thin stream of carbon dioxide.

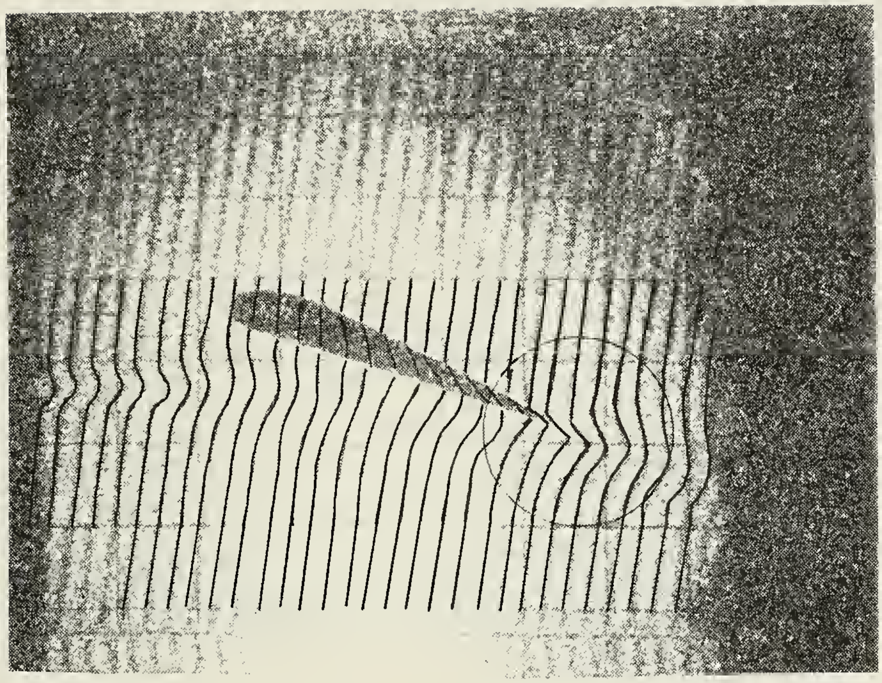

Figure 2(b). Photograph of a reconstructed hologram of a two-dimensional wing in a uniform flow of 6 fps. Notice the Kutta Condition at the trailing edge of the profile.

[illegible]

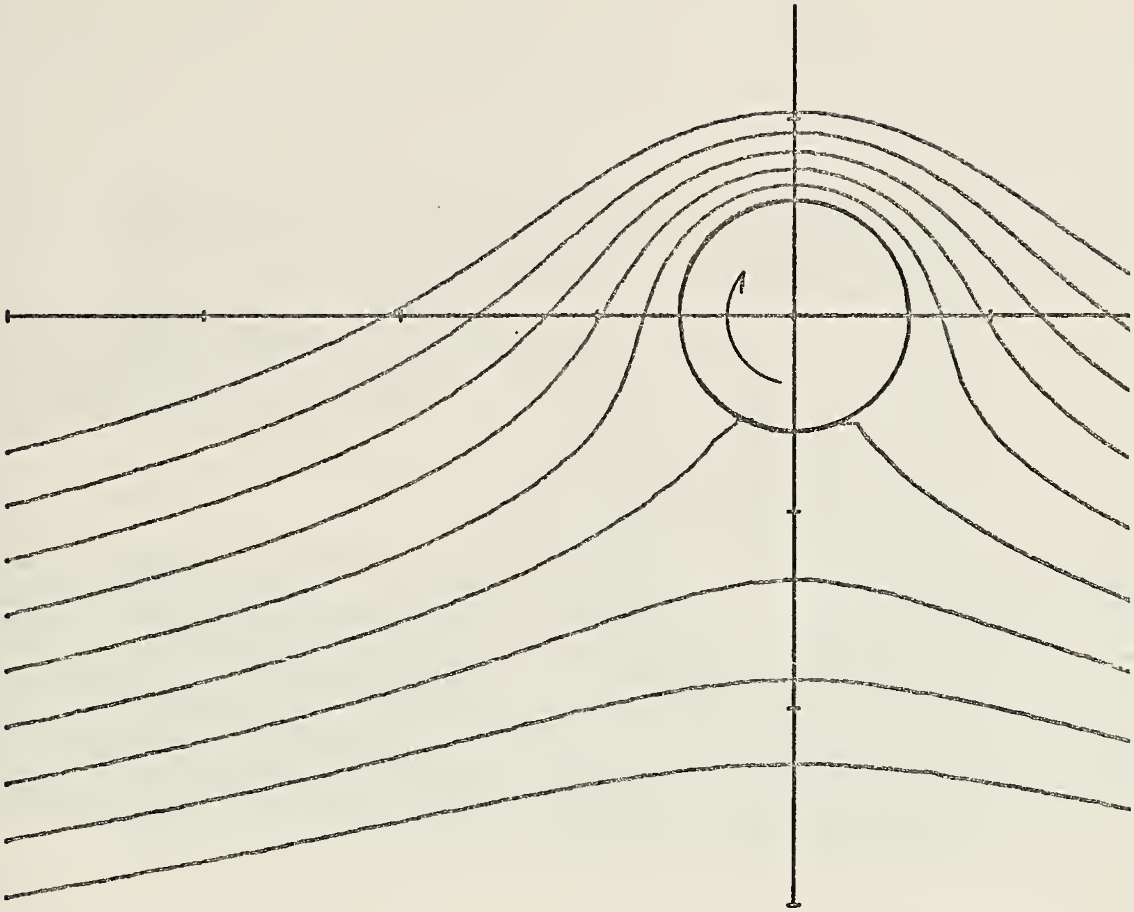

Figure 2(c). Graphical output of potential flow program given in Appendix A. The stream functions are for a uniform velocity of 10 ft/sec around a cylinder of 1.18 in. with a clockwise circulation of 75 ft^2/sec.

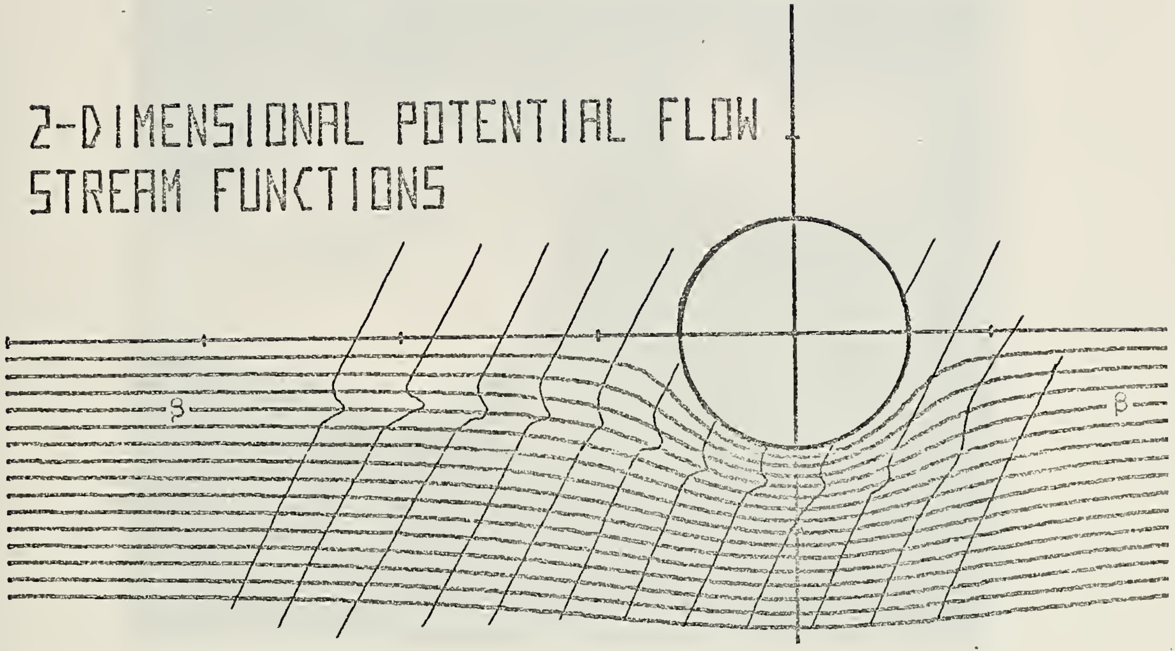

Figure 2(d). Fringe lines of Fig. 2(a) superimposed on graphical output of stream functions around a cylinder.

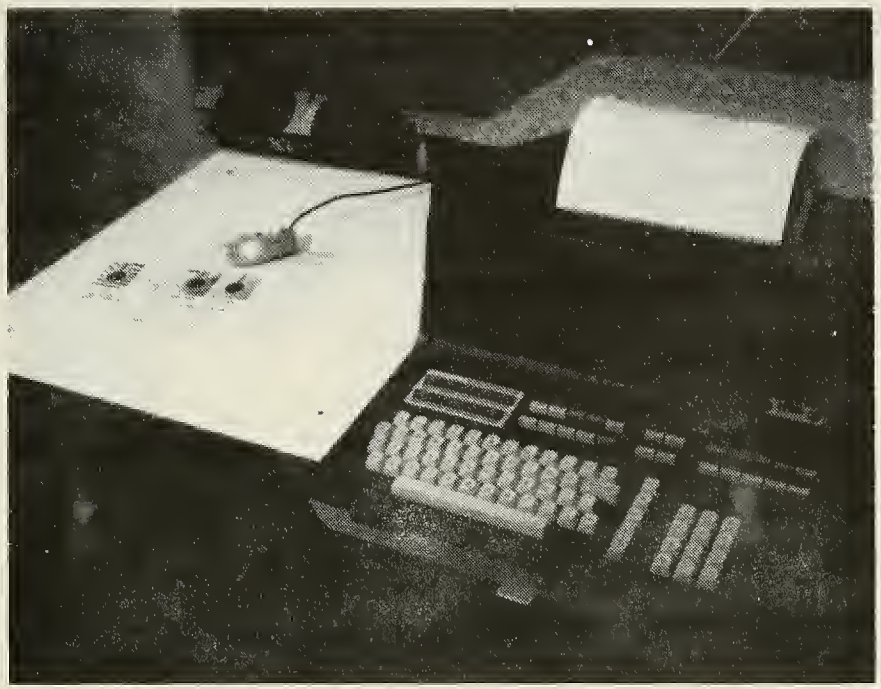

Figure 3. A view of the Hewlett Packard digitizer, printer and calculator. On the digitizing table is a finite frozen fringe hologram with a transparent grid and the electronic cursor. To the rear of the table is the acoustic coupler.

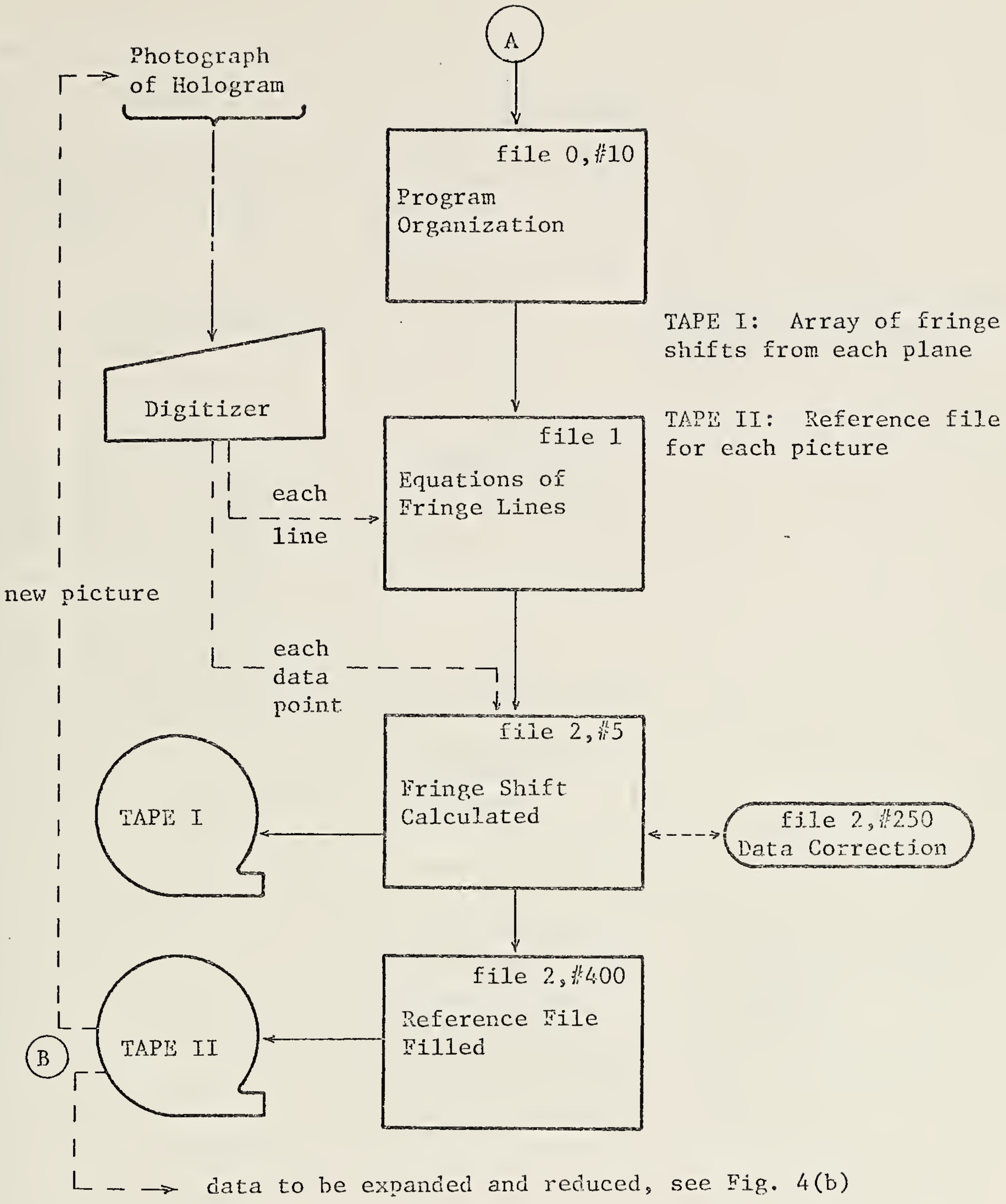

Figure 4(a). Flow diagram of data transfer program. Dashed lines are manual operations. Program file number and statement number is in the right upper corner of each operation.

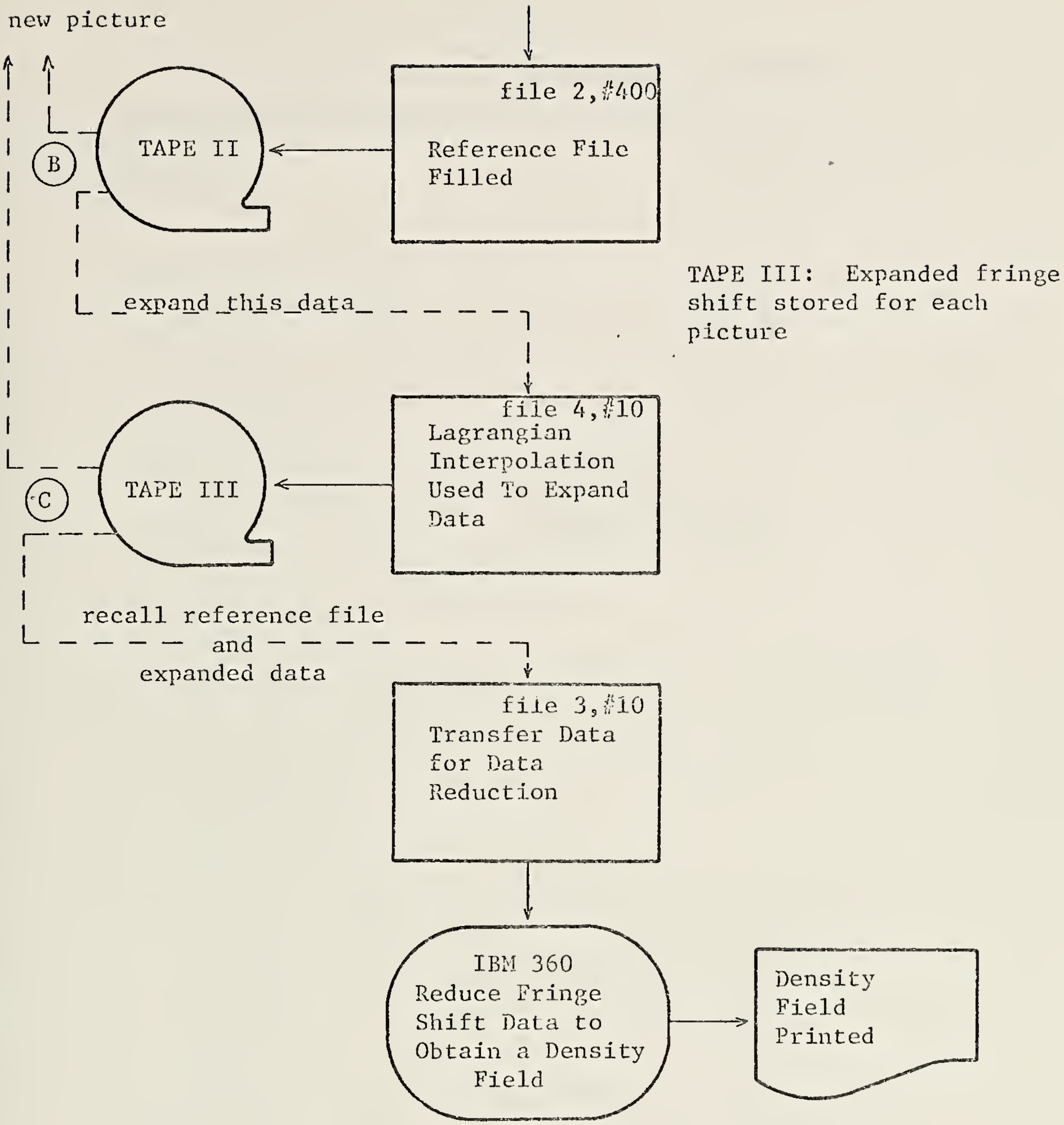
new picture
TAPE II
B
file 2,#400
Reference File Filled
expand this data
TAPE III: Expanded fringe shift stored for each picture
file 4,#10
Lagrangian Interpolation Used To Expand Data
TAPE III
C
recall reference file and expanded data
file 3,#10
Transfer Data for Data Reduction
IBM 360
Reduce Fringe Shift Data to Obtain a Density Field
Density Field Printed

Figure 4(b). Flow diagram of the data transfer program. During the file 3 operation the calculator is acting as a terminal.

APPENDIX A

Listing of Potential Flow Program

This program calculates stream functions around a cylinder with circulation.

```
10 REM****2-D FLOW****
12 DIM A[250]
20 DISP "ENTER XMIN,XMAX,YMIN,YMAX";
30 INPUT X1,X2,Y1,Y2
40 SCALE X1,X2,Y1,Y2
50 XAXIS 0,+1
60 YAXIS 0,+1
70 REM FOR TITLE TYPE"LETTER"
80 REM POSITION WITH DISPLAY KEYS
90 REM "EXECUTE"IS RETURN/LINE FEED
100 REM "STOP"TERMINATES LETTER MODE
110 LABEL (*,4,2,0,2/3)
120 DISP "  TYPE TITLE"
130 LETTER
140 DISP "INCR Y(.3),Z(<250),PHI CONV(.05)";
150 INPUT Y6,Z,Z1
160 DISP "ENTER P1CTURE DIA&ACT VELOCITY";
170 INPUT R2,U1
175 Y=0.5
180 U=R2*U1
190 R=R2/2
200 T=-4*PI*R*U
210 DISP "CRITICAL CIRCULATION IS"T
220 WAIT 4000
230 DISP "ENTER CIRCULATION(CW 1S NEG)";
240 INPUT T
250 DISP "FOR CIRCLE GO...CONT 590"
260 STOP
270 PLOT X1,0,+1
275 DISP "POSITIVE PHI BELOW X AXIS"
276 WAIT 4000
280 DISP "ENTER PHI,PHI END,PHI INCR";
290 INPUT P,P2,P3
300 PLOT X1,0,+1
308 I=1
309 I1=(X2-X1)/Z
310 FOR X=X1 TO X2 STEP I1
320 Y5=Y6
330 IF X=0 THEN 350
340 GOSUB 440
350 A[I]=Y
351 DISP I
```

```
355 I=I+1
360 NEXT X
361 I=1
362 DISP "PHI="P
363 WAIT 500
365 FOR X=X1 TO X2 STEP I1
366 PLOT X,A[I],+2
367 I=I+1
368 NEXT X
370 PEN
380 IF P=P2 THEN 420
390 P=P+P3
410 GOTO 300
420 STOP
440 N=0
450 B=SQR(X*X+Y*Y)
460 A=U*Y-(U*R*R*Y)/(X*X+Y*Y)-T*LOG(B/R)/(2*PI)
465 A=-A
470 Q=A-P
480 IF ABS(A-P) <= Z1 THEN 580
490 IF Q*N >= 0 THEN 510
500 Y5=Y5/2
510 IF A<P THEN 550
520 Y=Y+Y5
530 N=Q
540 GOTO 450
550 Y=Y-Y5
560 N=Q
570 GOTO 450
580 RETURN
590 PLOT -R,0,+1
600 FOR X=-R TO R STEP 0.01
610 Y=SQR(R*R-X*X)
620 PLOT X,Y,+2
630 NEXT X
640 PLOT R,0,+2
650 FOR X=R TO -R STEP -0.01
660 Y=-SQR(R*R-X*X)
670 PLOT X,Y,+2
680 NEXT X
690 PLOT -R,0,+2
700 PEN
710 GOTO 270
720 END
```

APPENDIX B

Listing of Calculator Data Transfer Programs

B.1 Listing of HP File 0. This program prints the organization of the files in the tape cassette. By executing "Run 200" the stored data of any picture may be printed.

```
10 REM THIS PROGRAM BY DAVID POPE USES A CALCULATER, PRINTER
11 REM AND DIGITIZER (HP9830A,HP9866A,HP9864A) TO RECORD THE
12 REM FRINGE SHIFT FROM A PHOTO OF A RECONSTRUCTED HOLOGRAM
13 REM THE INFORMATION IS FED INTO THE CP/CMS SYSTEM OF AN
14 REM IBM 360 COMPUTER WHICH DOES THE ACTUAL DATA REDUCTION
15 REM THE NORMAL FLOW OF DATA IS:FILE 0,FILE 1,FILE 2,
16 REM FILE 4, AND THEN FILE 3 FOR THE CP/CMS HOOKUP.
19 FIXED 0
20 DISP "ENTER TIME DAY MONTH YEAR";
30 INPUT Y1,Y2,Y3,Y4
40 PRINT "TIME"Y1"DAY"Y2"MONTH"Y3"YEAR"Y4
50 PRINT "DIRECTIONS AND ORGANIZATION"
70 PRINT "UP TO 20 PLANES WITH 20 POINTS PER PLANE"
80 PRINT "DATA FOR 9 PICTURES MAY BE GATHERED AND STORED"
90 PRINT "FILE 0:ORGANIZATION, READOUT                       "
100 PRINT "FILE 1:EQUATIONS FOR UP TO 20 LINES"
110 PRINT "FILE 2:FRINGE DISPLACEMENT FROM THE LINES"
120 PRINT "FILE 3:MATE WITH CP/CMS SYSTEM"
130 PRINT "FILE 4:LAGRANGIAN INTERPOLATION
140 PRINT "FILE 5:COMPARES TWO PLANES, REDEFINES DATA FILES"
160 PRINT "FILE 6:STREAM FUNCTIONS FOR 2-D POTENTIAL FLOW"
181 PRINT "FILES 7 ON ARE DATA STORAGE FILES"
183 PRINT " STORED DATA READOUT PRESS LOAD0 EX,RUN200 EX"
190 LOAD 1
200 REM*****READOUT OF STORED DATA*****
220 DIM DS[41],SI[5],TS[6],QS[150]
230 DISP "ENTER PICTURE NUMBER";
235 FIXED 0
240 INPUT P
241 PRINT "PICTURE NUMBER"P
242 FIXED 5
250 Z2=P*23-16
260 LOAD  DATA Z2,S
270 LOAD  DATA (Z2+1),T
271 LOAD  DATA (Z2+2),Q
273 PRINT "INTERPOLATED DATA FOR CP/CMS"
```

```
274 PRINT "THIS IS FROM PLANE"Q[2]
275 PRINT "POINT #"(Q[1]+3)"SHOULD BE 9.99000"
283 FOR I=1 TO (Q[1]+3)
284 PRINT I,Q[I]
285 NEXT I
290 Z=S[1]
301 PRINT "NUMBER OF PLANES ="S[1]
302 PRINT "MODE OF OPERATION ="S[2]
303 PRINT "NUMBER OF DATA POINTS FOR CP/CMS ="S[3]
304 PRINT "NUMBER OF VIEWS ="S[4]
305 PRINT "SYMMETERY OF FIELD ="S[5]
306 PRINT "REFERENCE DENSITY (MG/CC) ="T[1]
307 PRINT "WAVELENGTH IN MICRONS ="T[2]
308 PRINT "RMAX (CM) ="T[3]
309 PRINT "FILTER ="T[4]
310 PRINT "TH (VIEWING ANGLE IN DEG) ="T[5]
311 PRINT "DATA SYMMETERY ="T[6]
370 FOR Z1=1 TO Z
380 Z2=Z1+(P*23)-14
390 LOAD  DATA Z2,D
400 PRINT D[1]"DATA POINTS IN PLANE"Z1
410 FIXED 3
420 I=D[1]*2
430 FOR K=2 TO I STEP 2
440 J=K+1
450 PRINT "ELEVATION="D[K],"SHIFT="D[J]
460 NEXT K
470 NEXT Z1
471 PRINT "**************************************************
472 PRINT
473 PRINT
480 STOP
500 END
```

B.2 Listing of HP File 1. This program calculates the equations for up to 20 fringe lines in each picture. The mean of the slope and the differences from the mean of each slope is also printed. Two data points are entered through the digitizer to calculate each fringe line.

```
10 COM ZI,J1,J2,AS[20],BS[20],CS[20]
19 PRINT "FOR CORRECTIONS YOU MUST START OVER"
20 DISP "ORIENT THE CURVES"
30 WAIT 2000
40 DISP "ENTER THE ORGIN,PRESS..CONT.EX"
50 STOP
60 DISP "ENTER SECOND POINT ON HORIZ AXIS"
70 WAIT 2000
80 WRITE (9,*)
90 ENTER (9,*)X,Y
100 J1=SIN(ATN(Y/X))
110 J2=COS(ATN(Y/X))
120 DEG
130 PRINT "SLOPE OF THE PHOTO IS"(ATN(Y/X))"DEGREES"
140 DISP "# OF FRINGE LINES (MAX OF 20)";
150 INPUT N
160 DISP "NUMBER OF PLANES,MAX OF 20";
170 INPUT Z
180 PRINT "NUMBER OF LINES"N
190 PRINT "NUMBER OF PLANES"Z
200 DIM MS[20]
210 E=0
220 FOR I=1 TO N
221 DISP "FIRST POINT FOR LINE"I
222 WAIT 1000
230 WRITE (9,*)
240 ENTER (9,*)X,Y
260 X1=X*J2+Y*J1
270 Y1=Y*J2-X*J1
280 DISP "SECOND POINT LINE"I
281 WAIT 1000
```

```
290 WRITE (9,*)
300 ENTER (9,*)X,Y
320 X2=X*J2+Y*J1
330 Y2=Y*J2-X*J1
340 M[I]=(Y2-Y1)/(X2-X1)
350 E=E+M[I]
360 R=SQR(M[I]↑2+1)
370 A[I]=M[I]/R
380 B[I]=(-1)/R
390 C[I]=(Y1-M[I]*X1)/R
400 DISP "LINE      "I"       IS ENTERED"
410 WAIT 1000
420 NEXT I
430 N1=E/N
431 FIXED 4
432 PRINT "THE MEAN OF THE SLOPES IS   "N1
440 S=0
450 FOR I=1 TO N
460 PRINT "LINE"I;"DIFFERENCE FROM MEAN IS"(M[I]-N1)
470 S=S+(M[I]-N1)↑2
480 NEXT I
490 D=SQR(S/N)
500 PRINT "STANDARD DEVIATION OF SLOPES"D
510 DISP "SATISFIED WITH SLOPES?,..CONT.EX"
530 STOP
540 LOAD 2
```

B.3 Listing of HP File 2. For each data point entered this program calculates the fringe shift from the appropriate fringe line. The array of fringe shifts from each plane are stored on tape. A reference file is also filled and stored on tape.

```
5 COM ZI;J1,J2;AS[20],BS[20];CS[20]
10 DIM GS[41]
15 PRINT "CORRECT EACH PLANE BEFORE MOVING TO NEXT PLANE"
20 PRINT "IF POINT CORRECTION THEN...STOP CONT 250"
25 DISP "CORRECTION...STOP CONT 250"
30 WAIT 5000
35 DISP "ENTER PICTURE NUMBER";
40 INPUT P
45 PRINT "PICTURE NUMBER"P
50 Z1=1
60 Z2=Z1+(P*23)-14
65 FIND Z2
66 DISP "START ENTERING POINTS"
67 WAIT 1500
70 PRINT "DISPLACEMENT IN PLANE"Z1
71 PRINT "POINT #        ELEVATION                    SHIFT
75 DISP "NUMBER OF POINTS IN PLANE"Z1;
80 INPUT N
85 G[1]=N
90 J=1
95 I=1
100 WRITE (9,*)
105 ENTER (9,*)X,Y
125 X1=X*J2+Y*J1
130 Y1=Y*J2-X*J1
135 J=J+1
140 G[J]=Y1
145 J=J+1
150 G[J]=A[I]*X1+B[I]*Y1+C[I]
155 K=J-1
160 FIXED 4
165 REM G(1) IS THE NUMBER OF POINTS IN THE PLANE
170 REM G(J) IS THE SHIFT,G(K) IS THE ELEVATION
175 PRINT I,TAB10,"Y="G[K],TAB36;G[J]
180 IF I=N THEN 191
185 I=I+1
190 GOTO 100
```

```
191 WAIT 4000
195 STORE  DATA Z2,G
200 IF Z1=Z THEN 215
205 Z1=Z1+1
210 GOTO 60
215 DISP "SATISFIED WITH THESE POINTS?"
220 WAIT 3000
225 DISP " CONT...EX"
230 STOP
235 REM   EACH FILE CONTAINS ONE PLANE
240 GOTO 395
245 REM*****CORRECTIONS*****
250 DISP "ENTER LINE NUMBER";
255 INPUT I1
260 WRITE (9,*)
265 ENTER (9,*)X,Y
285 X1=X*J2+Y*J1
290 Y1=Y*J2-X*J1
295 R=2*I1
300 G[R]=Y1
305 R=R+1
310 G[R]=A[I1]*X1+B[I1]*Y1+C[I1]
315 PRINT "CORRECTION PLANE"Z1"LINE"I1,"Y="Y1,"SHIFT="G[R]
320 DISP "IF SATISFIED GO...CONT 195"
325 WAIT 5000
330 GOTO 250
395 REM ****FILL THE REFERENCE FILE****
400 DIM SI[5],TS[6]
415 Z2=P*23-16
420 FIND Z2
425 S[1]=Z
430 DISP "ENTER MODE OF OPERATION(3)";
435 INPUT S[2]
440 DISP "ENTER NUMBER OF VIEWS(1)";
445 INPUT S[4]
450 DISP "ENTER SYMMETRY OF FIELD(0)";
455 INPUT S[5]
465 DISP "ENTER # OF POINTS FOR CP/CMS";
470 INPUT S[3]
505 STORE  DATA Z2,S
510 DISP "ENTER REFERENCE DENSITY(MG/CC)";
515 INPUT T[1]
520 DISP "ENTER WAVELENGTH IN MICRONS";
525 INPUT T[2]
530 DISP "ENTER RMAX(CM)";
535 INPUT T[3]
540 DISP "ENTER FILTER";
545 INPUT T[4]
550 DISP "ENTER TH(VIEWING ANGLE IN DEG)";
555 INPUT T[5]
560 DISP "ENTER DATA SYMMETRY(0)";
565 INPUT T[6]
```

```
570 Z2=Z2+1
575 STORE  DATA Z2;T
580 PRINT "IF YOU WANT TO REDUCE THIS PICTURE THEN...LOAD 5
590 PRINT "IF YOU WANT TO GATHER MORE DATA FOR NEXT PICTURE
600 PRINT "    "
610 DISP "DATA STORED FOR PICTURE"P
620 STOP
630 END
```

B.4 Listing of HP File 3. This program recalls the array of expanded data from the tape cassette and then the calculator, acting as a terminal, automatically sends the data to FILE FT03F001 in the IBM computer.

```
5 PRINT "FOR DIRECTIONS PRESS LIST10,110...EX"
10 REM SET ACOUSTIC COUPLER DUPLEX TO 1/2 AND TURN ON
20 REM DIAL 2611 ON PHONE AND PLACE IN COUPLER
21 REM YOU SHOULD HEAR A HIGH PITCHED TONE
30 REM RED LIGHT ON, THEN THE COUPLER IS ON
31 REM WHITE LIGHT ON WHEN TRANSMITTING/RECIEVING
40 REM TYPE IN "TERM...EX"
50 REM "CP-67 ONLINE" APPEARS IF CP/CMS IS READY
60 REM TYPE LOGIN PROCEDURE
70 REM TYPE "IPL CMS"
80 REM TYPE "TTY FILE FT03F001 70"
81 REM LAST # IN FT03F.. SHOULD BE PICTURE #
82 REM SHOULD DISP"READY PAPER TAPE IN READER..."
83 REM TYPE & TRANSMIT TWO VIRTUAL CARDS WORTH OF TITLE
90 REM THIS IS THE READIN DATA FILE FOR THE CP/CMS
91 REM TYPE IN TITLE(#1) AND TRANSMIT
92 REM TYPE IN TITLE(#2) AND TRANSMIT
100 REM PRESS "RUN...EX";THIS STARTS THE CALCULATER
110 REM TRANSMIT ANYTHING "CONTROL(F6)-S-TRANSMIT(F9)
120 DIM AI[5],BS[6],SS[150]
125 FIXED 5
130 DISP "ENTER PICTURE NUMBER";
140 INPUT P
150 Z2=P*23-16
160 LOAD  DATA Z2,A
170 LOAD  DATA (Z2+1),B
180 LOAD  DATA (Z2+2),S
183 A[3]=INT(S[1])
184 PRINT "YOU ARE REDUCING"A[3]"DATA POINTS IN CP/CMS"
185 PRINT
190 DISP "ARE YOU READY TO SEND DATA?"
200 WAIT 3000
```

```
205 A[3]=INT(S[1])
210 DISP "IF SO ,PRESS CONT...EX"
220 STOP
230 WRITE (4,340)A[1],A[2],A[3],A[4],A[5],19
235 PRINT A[1];A[2];A[3];A[4];A[5]
240 WAIT 3000
250 WAIT 3000
260 WRITE (4,350)B[1],B[2],B[3],B[4],B[5],B[6],19
265 PRINT B[1];B[2];B[3];B[4];B[5];B[6]
266 PRINT
270 WAIT 3000
280 WAIT 3000
290 G=INT((A[3]/6)+1)
295 G=G+1
300 FOR I=1 TO (G*6) STEP 6
310 WRITE (4,360)S[I],S[I+1],S[I+2],S[I+3],S[I+4],S[I+5],19
315 PRINT S[I];S[I+1];S[I+2];S[I+3];S[I+4];S[I+5]
320 WAIT 3000
330 WAIT 3000
340 FORMAT 5F8.0,B
350 FORMAT 6F10.5,B
360 FORMAT 6F11.5,B
380 NEXT I
390 WRITE (4,395)19,19,19,19,19,19
395 FORMAT B,B,B,B,B,B
400 PRINT "DATA SENT TO FILE IN CP/CMS"
401 PRINT "TO REDUCE DATA(EXECUTE POPE1)     $ POPE1"
402 PRINT "OUTPUT IN FILE FT08F001"
403 PRINT
410 STOP
420 END
```

B.5 Listing of HP File 4. This program expands the fringe shift data by using Lagrangian interpolation. The array of expanded fringe data is stored on the tape cassette.

```
10 DIM XS[20],YS[20],DS[41],GS[150],UI[20]
15 PRINT "TO STOP PRINTING ....DEL 520,520..EX"
16 PRINT
17 WAIT 5000
20 DISP "ENTER PICTURE & PLANE #";
30 INPUT P1,Z2
40 DISP "ENTER # OF PICTURES";
50 INPUT Q
60 PRINT "# OF PICTURES TO BE REDUCED IS"Q
70 H=U=0
80 P=R=U[1]=1
90 N=S7=0
100 FOR I=1 TO 150
110 G[I]=9.99
120 NEXT I
190 PRINT "PICTURE"P1,"PLANE"Z2
200 Z3=Z2+P1*23-14
210 LOAD  DATA Z3,D
220 K=D[1]
230 J2=2
240 N=0
250 X=D[J2]
260 Y=D[J2+1]
270 J2=J2+2
280 N=FNZ1
290 IF N<K THEN 250
300 IF H#0 THEN 415
320 GOSUB 660
330 DISP "# OF POINTS TO USE (<7)";
340 INPUT M
350 FOR I=1 TO M
360 DISP "USE POINT #";
370 INPUT U[I]
374 FIXED 0
375 PRINT "POINT"U[I]"USED"
376 FIXED 4
380 NEXT I
390 U=2
400 DISP "MIN ELEV.,MAX ELEV.,# OF POINTS";
410 INPUT A7,B7,S8
415 PRINT "INTERPOLATION BASED ON"M"DATA POINTS"
420 PRINT "MIN ELEVATION"A7
430 PRINT "MAX ELEVATION"B7
440 PRINT "# OF POINTS"S8
```

```
460 G[2]=Z2
470 I1=2
480 S7=(B7-A7)/(S8-1)
500 FOR X=A7 TO B7 STEP S7
510 G[I1+1]=FNAX
515 DISP (I1-1)
520 PRINT (I1-1),X,G[I1+1]
525 G[1]=I1-1
530 I1=I1+1
540 NEXT X
590 STORE  DATA (P1*23-14),G
591 PRINT "*****"G[1]"POINTS GENERATED AND STORED*****"
592 PRINT
600 H=H+1
610 IF H=Q THEN 640
620 P1=P1+1
630 GOTO 80
640 DISP "END OF LA. INTER."
641 WAIT 4000
642 PRINT "TO REDUCE DATA LOAD 3"
643 PRINT
650 STOP
660 PRINT "POINT #";"     X";"     Y"
665 FIXED 4
670 FOR I=1 TO N
680 PRINT I,X[I],Y[I]
690 NEXT I
695 PRINT
700 RETURN
710 END
720 DEF FNZ(Z)
730 FOR I=N TO 1 STEP -1
740 IF X<X[I] THEN 790
750 X[I+1]=X
760 Y[I+1]=Y
770 RETURN N+1
780 X[I+1]=X[I]
790 Y[I+1]=Y[I]
800 NEXT I
810 I=0
820 GOTO 750
830 END
840 DEF FNA(Z)
860 S=0
980 FOR I2=1 TO M
990 T=1
1000 I=U[I2]
1010 FOR J1=1 TO M
1020 J=U[J1]
1030 GOSUB 1080
```

```
1040 NEXT J1
1050 S=S+T*Y[ I ]
1060 NEXT 12
1070 GOTO 1120
1080 IF X[ I ]=X[ J ] THEN 1110
1090 T=T*(Z-X[ J ])/(X[ I ]-X[ J ])
1110 RETURN
1115 T=0
1120 RETURN S
1130 END
```

B.6 Listing of HP File 5. The beginning of this program compares two pictures at one plane. The second section of this program redefines all of the data files.

```
10 REM COMPARE 2 PLANES...RUN,EX
20 REM REDEFINE DATA FILES...RUN340,EX
30 REM POTENTIAL FLOW OVER CYLINDER...RUN570,EX
40 DISP "COMPARE THE TWO PLANES"
50 DIM ES[41],FS[41]
60 WAIT 3000
70 DISP "ENTER THE PLANE NUMBER";
80 INPUT Z
90 DISP "ENTER PICTURE NUMBERS";
100 INPUT P1,P2
110 PRINT "PLANE"Z"PICTURES"P1,P2
120 Z1=Z+(P1*23)-14
130 Z2=Z+(P2*23)-14
140 LOAD  DATA Z1,D
150 LOAD  DATA Z2,E
160 FIXED 4
170 IF D[1]<E[1] THEN 230
180 R=E[1]*2+1
190 FOR I=2 TO R
200 F[I]=D[I]-E[I]
210 NEXT I
220 GOTO 270
230 R=D[1]*2+1
240 FOR I=2 TO R
250 F[I]=D[I]-E[I]
260 NEXT I
270 FOR I=2 TO R STEP 2
280 J=I+1
290 PRINT "DIFF"F[I],TAB20,F[J]
300 NEXT I
310 STOP
320 GOTO 40
330 END
```

```
340 REM ****REDEFINES DATA FILES****
350 FIND 7
360 FIND 7
370 FOR P=1 TO 10
380 Z2=P*23-16
390 FIND Z2
400 DISP "PICTURE IS "P
410 WAIT 500
420 MARK 1,5
430 FIND (Z2+1)
440 DISP "PICTURE   "P"   A"
450 WAIT 200
460 MARK 1,12
470 FIND (Z2+2)
480 DISP "   PICTURE "P"    B"
490 WAIT 200
500 MARK 1,300
510 FIND (Z2+3)
520 DISP "   PICTURE"P"   C"
530 MARK 20,82
540 NEXT P
550 STOP
560 END
```

APPENDIX C

Printed Results of the Calculator Programs

C.1 Results from File 0, File 1, and File 2.

```
TIME 1110    DAY 14   MONTH 5    YEAR 1974
DIRECTIONS AND ORGANIZATION
UP TO 20 PLANES WITH 20 POINTS PER PLANE
DATA FOR 9 PICTURES MAY BE GATHERED AND STORED
FILE 0:ORGANIZATION, READOUT, COMPARE 2 PICTURES
FILE 1:EQUATIONS FOR UP TO 20 LINES
FILE 2:FRINGE DISPLACEMENT FROM THE LINES
FILE 3:  MATE WITH CP/CMS SYSTEM
FILE 4:LAGRANGIAN INTERPOLATION(NORMALLY NOT USED)
FILE 5:LAGRANGIAN INTERPOLATION USED
FILE 6: COMPARE TWO PICTURES AT A PLANE
FILES 7 ON ARE DATA STORAGE FILES
 STORED DATA READOUT PRESS LOAD0 EX,RUN200 EX
FOR CORRECTIONS YOU MUST START OVER
SLOPE OF THE PHOTO IS 9.700391944   DEGREES
NUMBER OF LINES 5
NUMBER OF PLANES 3
THE MEAN OF THE SLOPES IS   -0.0315
LINE 1.0000  DIFFERENCE FROM MEAN IS 0.0041
LINE 2.0000  DIFFERENCE FROM MEAN IS-0.0095
LINE 3.0000  DIFFERENCE FROM MEAN IS 0.0273
LINE 4.0000  DIFFERENCE FROM MEAN IS-0.0330
LINE 5.0000  DIFFERENCE FROM MEAN IS 0.0111
STANDARD DEVIATION OF SLOPES,0.0203
CORRECT EACH PLANE BEFORE MOVING TO NEXT PLANE
IF POINT CORRECTION THEN...STOP CONT 250
PICTURE NUMBER 3
DISPLACEMENT IN PLANE 1
POINT #       ELEVATION                SHIFT
 1.0000        Y= 0.3156           0.0085
 2.0000        Y= 0.3567           0.0016
 3.0000        Y= 0.3863           0.0378
 4.0000        Y= 0.4175           0.0330
 5.0000        Y= 0.4372           0.0722
DISPLACEMENT IN PLANE 2.0000
POINT #       ELEVATION                SHIFT
 1.0000        Y= 0.2597           0.0537
 2.0000        Y= 0.2893           0.0528
 3.0000        Y= 0.2992           0.1233
 4.0000        Y= 0.3107           0.1146
```

```
  DISPLACEMENT IN PLANE 3.0000
  POINT #        ELEVATION                   SHIFT
   1.0000         Y= 0.2827               0.0198
   2.0000         Y= 0.3238               0.0022
   3.0000         Y= 0.3650               0.0559
   4.0000         Y= 0.4044              -0.0047
   5.0000         Y= 0.4258               0.0677

IF YOU WANT TO REDUCE THIS PICTURE THEN...LOAD 5
IF YOU WANT TO GATHER MORE DATA FOR NEXT PICTURE...LOAD 1

TO STOP PRINTING ....DEL 520;520..EX
# OF PICTURES TO BE REDUCED IS 1
PICTURE 3       PLANE 2
POINT #               X               Y
 1.0000           0.2597          0.0537
 2.0000           0.2893          0.0528
 3.0000           0.2992          0.1233
 4.0000           0.3107          0.1146

POINT 1     USED
POINT 2     USED
POINT 3     USED
POINT 4     USED
INTERPOLATION BASED ON 4.0000  DATA POINTS
MIN ELEVATION 0.2500
MAX ELEVATION 0.3200
# OF POINTS 13.0000
 1.0000           0.2500          0.3274
 2.0000           0.2558          0.1389
 3.0000 .         0.2617          0.0223
 4.0000           0.2675         -0.0354
 5.0000           0.2733         -0.0470
 6.0000           0.2792         -0.0254
 7.0000           0.2850          0.0164
 8.0000           0.2908          0.0657
 9.0000           0.2967          0.1094
 10.0000          0.3025          0.1348
 11.0000          0.3083          0.1289
 12.0000          0.3142          0.0789
 13.0000          0.3200         -0.0282
***** 13.0000     POINTS GENERATED AND STORED*****

TO REDUCE DATA LOAD 3
```

C.2 Printed output of readout of stored data. Listing of stored data obtained by executing "Run 200" on File 0.

```
PICTURE NUMBER 3
INTERPOLATED DATA FOR CP/CMS
THIS IS FROM PLANE 2.00000
POINT # 16.00000   SHOULD BE 999999.000000
 1.00000        13.00000
 2.00000        2.00000
 3.00000        0.32742
 4.00000        0.13893
 5.00000        0.02230
 6.00000       -0.03539
 7.00000       -0.04700
 8.00000       -0.02544
 9.00000        0.01642
 10.00000       0.06567
 11.00000       0.10943
 12.00000       0.13481
 13.00000       0.12893
 14.00000       0.07888
 15.00000      -0.02821
 16.00000       999999.00000
NUMBER OF PLANES = 3.00000
MODE OF OPERATION = 3.00000
NUMBER OF DATA POINTS FOR CP/CMS = 13.00000
NUMBER OF VIEWS = 1.00000
SYMMETERY OF FIELD = 0.00000
REFERENCE DENSITY (MG/CC) = 1.74500
WAVELENGTH IN MICRONS = 0.69440
RMAX (CM) = 2.78000
FILTER = 0.00000
TH (VIEWING ANGLE IN DEG) = 0.00000
DATA SYMMETERY = 0.00000
 5.00000    DATA POINTS IN PLANE 1.00000
ELEVATION= 0.316              SHIFT= 0.008
ELEVATION= 0.357              SHIFT= 0.002
ELEVATION= 0.386              SHIFT= 0.038
ELEVATION= 0.418              SHIFT= 0.033
ELEVATION= 0.437              SHIFT= 0.072
 4.000   DATA POINTS IN PLANE 2.000
ELEVATION= 0.260              SHIFT= 0.054
ELEVATION= 0.289              SHIFT= 0.053
ELEVATION= 0.299              SHIFT= 0.123
ELEVATION= 0.311              SHIFT= 0.115
 5.000   DATA POINTS IN PLANE 3.000
ELEVATION= 0.283              SHIFT= 0.020
ELEVATION= 0.324              SHIFT= 0.002
ELEVATION= 0.365              SHIFT= 0.056
ELEVATION= 0.404              SHIFT=-0.005
ELEVATION= 0.426              SHIFT= 0.068
****************************************************  *******
```

APPENDIX D

Fortran Subroutine Which Inputs Data

This subroutine is in the Fortran data reduction program. The title, reference numbers, and fringe shift data are read from FILE FT03F001.

```
      SUBROUTINE DATA(IT,QA,QB,QS)
C     ****** THIS INPUTS DATA FROM FILE FT03F??? ******
      REAL IT(12),QB(6),QS(150)
      INTEGER QA(5)
      READ(3,981)(IT(I),I=1,12)
      WRITE(6,1000)(IT(I),I=1,12)
      READ(3,982)(QA(I),I=1,5)
      WRITE(6,1001)(QA(I),I=1,5)
      READ(3,983)(QB(I),I=1,6)
      WRITE(6,1002)(QB(I),I=1,6)
      ID=6*(QA(3)/6+1)
      DO 980 I=1,ID,6
      READ(3,984)(QS(I+J-1),J=1,6)
      WRITE(6,1003)(QS(I+J-1),J=1,6)
1000  FORMAT(1X,6A8)
1001  FORMAT(1X,5I8)
1002  FORMAT(1X,6F10.5)
1003  FORMAT(1X,6F11.5)
980   CONTINUE
981   FORMAT(6A8)
982   FORMAT(5I8)
983   FORMAT(6F10.5)
984   FORMAT(6F11.5)
      IX=QA(3)
      DO 985 I=1,IX
      QS(I)=QS(I+2)
  985 CONTINUE
      RETURN
      END
```

APPENDIX E

Listing of Data in FILE FT03F001

This is the data as it appears in FILE FT03F001. An existing fortran program reads its input data from this file and calculates a density field. The first two lines are output title, the third and fourth lines are reference data and line five on is the expanded fringe shift data to be reduced.

```
THIS IS A DENSITY FIELD CALCULATION
REDUCED FROM FRINGE SHIFT DATA
      1         3        13        1        0
   1.74500    0.69440    2.00000   0.00000   0.00000   0.00000
   13.00000    2.00000     0.32742     0.13893     0.02230    -0.03539
   -0.04700   -0.02544     0.01642     0.06567     0.10943     0.13481
    0.12893    0.07888    -0.02821     9.99999     9.99999     9.99999
    9.99999    9.99999     9.99999     9.99999     9.99999     9.99999
```

LIST OF REFERENCES

1. Collier, R., Burckhardt, C. B., and Lin, L. H., Optical Holography, Academic Press, New York, 1971.

2. Jones, H. W., "Application of Holographic Interferometry to Supersonic Flow Visualization of a Rear-Facing Step and Application to Current Data Reduction Techniques," Naval Postgraduate School, Monterey, Calif., 1974.

3. Everett, R., "Experimental Techniques in Holographic Interferometry," Naval Postgraduate School, Monterey, Calif., 1973.

4. Karamcheti, K., Principles of Ideal-Fluid Aerodynamics, John Wiley and Sons Inc., New York, 1966.

5. Van Houten, P., "The Application of Holographic Interferometry to the Determination of Discontinuous Three Dimensional Density Fields," A.E. Thesis, Naval Postgraduate School, Monterey, Calif., 1972.

6. Sweeney, D. W., "Interferometric Measurement of Three-Dimensional Temperature Fields," Ph.D. Thesis, University of Michigan, 1972.

7. Matulka, R. D., "The Application of Holographic Interferometry to the Determination of Asymmetric Three-Dimensional Density Field in Free Jet Flow," Ph.D. Thesis, Naval Postgraduate School, Monterey, Calif., 1970.

8. Jagota, R. C., "The Application of Holographic Interferometry to the Determination of the Flow Field Around a Right Circular Cone at Angle of Attack," A.E. Thesis, Naval Postgraduate School, Monterey, Calif., 1970.

DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	12
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Commander Naval Air Systems Command Department of the Navy Washington, D.C. 20360	
	ATTN: AIR 310	2
	AIR 604	2
4.	Department Chairman, Code 57 Department of Aeronautics Naval Postgraduate School Monterey, California 93940	1
5.	Professor D. J. Collins, Code 57Co Department of Aeronautics Naval Postgraduate School Monterey, California 93940	2
6.	Dr. H. J. Mueller Naval Air Systems Command AIR 310 Department of the Navy Washington, D.C. 20360	2
7.	Professor M. F. Platzer, Code 57Pl Department of Aeronautics Naval Postgraduate School Monterey, California 93940	1
8.	LT David L. Pope, USN 1204 Lake Shore Drive Gladstone, Michigan 49837	2
9.	Dr. Jorge E. Toni Ministerio De Defensa Zufriategui y Varela ARGENTINA	1
10.	Dean of Research Code 023A Naval Postgraduate School Monterey, California 93940	1

[illegible] 74 20978

153471

Thesis
P7405
c.1

Pope

Low speed flow visualization using holography and the development of a rapid data reduction system for holographic interferometry.

20978
[illegible] 74

153471

Thesis
P7405
c.1

Pope

Low speed flow visualization using holography and the development of a rapid data reduction system for holographic interferometry.

thesP7405
Low speed flow visulaization using holog
3 2768 001 92328 7
DUDLEY KNOX LIBRARY